2009

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Bioresource Technology 100 (2009) 3974–3981

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Determination of thermal properties of composting bulking materials

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ARTICLE INFO

Article history:
Received 28 February 2007
Received in revised form 7 November 2008
Accepted 20 November 2008
Available online 11 April 2009

Keywords:
Thermal properties
Compost bulking materials
Thermal conductivity
Thermal diffusivity
Volumetric heat capacity

ABSTRACT

Thermal properties of compost bulking materials affect temperature and biodegradation during the composting process. Well determined thermal properties of compost feedstocks will therefore contribute to practical thermodynamic approaches. Thermal conductivity, thermal diffusivity, and volumetric heat capacity of 12 compost bulking materials were determined in this study. Thermal properties were determined at varying bulk densities (1, 1.3, 1.7, 2.5, and 5 times uncompacted bulk density), particle sizes (ground and bulk), and water contents (0, 20, 50, 80% of water holding capacity and saturated condition). For the water content at 80% of water holding capacity, saw dust, soil compost blend, beef manure, and turkey litter showed the highest thermal conductivity (K) and volumetric heat capacity (C) (K: 0.12–0.81 W/m °C and C: 1.36–4.08 MJ/m^3 °C). Silage showed medium values at the same water content (K: 0.09–0.47 W/m °C and C: 0.93–3.09 MJ/m^3 °C). Wheat straw, oat straw, soybean straw, cornstalks, alfalfa hay, and wood shavings produced the lowest K and C values (K: 0.03–0.30 W/m °C and C: 0.26–3.45 MJ/m^3 °C). Thermal conductivity and volumetric heat capacity showed a linear relationship with moisture content and bulk density, while thermal diffusivity showed a nonlinear relationship. Since the water, air, and solid materials have their own specific thermal property values, thermal properties of compost bulking materials vary with the rate of those three components by changing water content, bulk density, and particle size. The degree of saturation was used to represent the interaction between volumes of water, air, and solids under the various combinations of moisture content, bulk density, and particle size. The first order regression models developed in this paper represent the relationship between degree of saturation and volumetric heat capacity (r = 0.95–0.99) and thermal conductivity (r = 0.84–0.99) well. Improved knowledge of the thermal properties of compost bulking materials can contribute to improved thermodynamic modeling and heat management of composting processes.

1. Introduction

Composting is the aerobic and biological organic matter decomposition process. Stabilization and pathogen destruction of organic waste occur during composting. The process has been accepted for treating many type of industrial and agricultural organic wastes owing to above merits. It also has been accepted as an option for disposal of the livestock mortalities (Blake and Donald, 1992; Sims et al., 1992; Cummins et al., 1994; Stanford et al., 2000; Fonstad et al., 2003).

Temperature is one of the important compost design and operational parameters as well as oxygen content, moisture content, and biodegradability. Temperature variations are a result of the thermal balance between heat generated by the microorganisms and heat lost through convection, conduction, evaporation, and radiation (Haug, 1993; Ahn et al., 2007). In order to succeed in a mortality composting process, it is necessary to keep a high temperature for sufficient time to inactivate and kill the pathogens (USEPA Class A requirement: 55 °C for at least three consecutive days, USEPA Class B requirement: at least 40 °C for 5 or more consecutive days, and exceed 55 °C at least 4 h during the 5 days period).

A robust understanding of the thermal balance in compost systems is required to design and properly control the composting processes. Thermal properties of compost bulking materials affect temperature and biodegradation during the composting process. Accurate thermal properties of compost feedstocks can contribute to practical thermodynamic approaches.

Thermal conductivity, thermal diffusivity, and specific heat capacity are the three important thermal properties regarding heat transfer analysis. These three thermal properties can be measured by several methods. Thermal conductivity can be measured by the steady and non-steady state (transient heat dissipation) methods (Mohsenin, 1980). Differential scanning calorimeter (DSC) has

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0960-8524/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.biortech.2008.11.056

been used by many researchers recently, because it supplies accurate and fast measurements of specific heat capacity (Tang et al., 1991). The third thermal property can be acquired by measuring any two of thermal properties based on the following relationship

$$\alpha = \frac{K}{\rho C_p} \tag{1}$$

where K is the thermal conductivity (W/m °C), α is the thermal diffusivity (m^2/s), ρ is the bulk density (kg m^{-3}), and C_P is the specific heat capacity (J/kg °C).

Although thermal properties are very important in composting, information on their values for various compost materials is lacking. Iwabuchi and Kamide (1993) reported the thermal conductivity of compost (dairy cattle manure and saw dust mixture) as 0.051 W/m °C dry and 0.096 W/m °C at 57% moisture content (w.b.). Iwabuchi et al. (1999) determined the thermal conductivity of dairy cattle manure and saw dust mixed compost as 0.05–0.202 W/m °C at volumetric water contents of 0–44.2%. The thermal property values presented by previous researchers are highly variable. For example, Ghaly et al. (2006) used the specific heat capacity value of compost as 870 J/kg °C, reported by Holman (2002), in their thermal balance work. While Cekmecelioglu et al. (2005) used a compost specific heat capacity value of 2719.5 J/kg °C, reported by Haug (1993), in their modeling. Discrepancy of thermal property values, which are applied to modeling work, may reduce the accuracy of model results.

Since the water, air, and solid materials have their own specific thermal property values, thermal properties of compost bulking materials vary with the ratio of those three materials by changing water content, bulk density, and particle size (Jiang et al., 1986; Holman, 2002; Labance et al., 2006). Generally, the thermal properties of compost bulking materials show specific trends of relationship with water content, bulk density, and particle size. The linear relationships of thermal conductivity and volumetric heat capacity with moisture content and bulk density have been reported by many researchers (Bristow, 1998; Yang et al., 2002; Chandrakanthi et al., 2005; Opoku et al., 2006). However, numerous studies have proven there is no relationship between the thermal diffusivity and both the moisture content and bulk density (Houkom et al., 1974; Verdonck et al., 1978; Jiang et al., 1986; Dutta et al., 1988; Bristow, 1998; Iwabuchi et al., 1999; Yang et al., 2002; Labance et al., 2006; Opoku et al., 2006).

As practical composting processes occur under the various interactions between each factor, it is important to obtain a representative model considering all factors combined. Labance et al. (2006) and Abu-Hamdeh et al. (2000) reported the effect of volumetric water content and bulk density on soil's thermal properties. Ochsner et al. (2001) considered the air-filled porosity and volumetric water content effect on soil thermal properties. Nevertheless, their research was not enough to present the combined effect of all factors on thermal properties. The concept of degree of saturation (Φ), suggested by Chandrakanthi et al. (2005), is used in this paper to show the combined effects of three factors on thermal conductivity and volumetric heat capacity.

The degree of saturation (Φ) is defined as the ratio of the volume of water (V_w) and the volume of total voids (V_v)

$$\Phi = \frac{V_w}{V_v} \tag{2}$$

where the total volume (V_t) is the sum of the volume of air (V_a), water (V_w), and solids (V_s)

$$V_t = V_a + V_w + V_s \tag{3}$$

and

$$V_v = V_a + V_w \tag{4}$$

The volume of air or air-filled porosity can be calculated

$$V_a = 1 - \rho_{wb} \cdot \left(\frac{MC}{\rho_w} + \frac{DM \cdot OM}{\rho_{om}} + \frac{DM \cdot (1 - OM)}{\rho_{ash}} \right) \tag{5}$$

Where MC: Moisture content (decimal, w.b.), OM: Organic matter (decimal, d.b.), DM: Dry matter (decimal, w.b.), ρ_{wb}: wet bulk density of sample (kg m^{-3}), ρ_w: 1000 kg m^{-3} (density of water), ρ_{vs}:1600 kg m^{-3} (density of organic material), ρ_{ash}: 2500 kg m^{-3} (density of inorganic material) (Rahman, 1995; Van Ginkel et al., 1999; Richard et al., 2002; Ahn et al., 2008a) V_W can be calculated with dry base gravimetric water content (MC_{db}) and dry bulk density (ρ_{db})

$$V_w = \frac{MC_{db} \cdot \rho_{db}}{\rho_w} \tag{6}$$

The first objective of this study was to determine the thermal conductivity, volumetric heat capacity, and thermal diffusivity of 12 compost bulking materials as a function of moisture content, bulk density and particle size. Thermal properties are measured with different methods, transient heat dissipation, steady state gradient methods and differential scanning calorimetry, are compared with each other and the general characteristics of each measurement method are presented. Finally, the representative models are derived from experimentally determined data to predict the thermal properties of each material at various combinations of moisture content, bulk density, and particle size.

Table 1
General characteristics of 12 compost-bulking materials ($N = 3$ for all tests).

Cover materials	VS[A] (d.b.,%)	WHC[B] (g·water/g·dry sample)	C_P[C] (J/g °C)	Dry bulk density(kg/m^3)		V_a[D] (%)	
				Bulk	Ground	Bulk	Ground
Wheat straw	91.9 ± 0.2	4.3 ± 0.1	1.63 ± 0.07	25.6 ± 3.7	121.6 ± 5.4	98.4 ± 0.2[a]	92.6 ± 0.3[b]
Saw dust	98.9 ± 0.0	3.4 ± 0.1	1.40 ± 0.05	102.5 ± 4.9	209.1 ± 5.1	93.6 ± 0.3 [a]	87.0 ± 0.3[b]
Soil compost blend	21.5 ± 0.7	0.5 ± 0.0	1.02 ± 0.03	749.6 ± 80.9	847.2 ± 14.7	66.4 ± 3.6 [a]	62.0 ± 0.7[b]
Silage	93.3 ± 0.6	3.8 ± 0.1	1.62 ± 0.07	106.2 ± 1.4	216.0 ± 0.9	93.5 ± 0.1[a]	86.8 ± 0.1[b]
Beef manure	64.9 ± 7.2	3.0 ± 0.0	1.76 ± 0.18	212.4 ± 41.0	442.4 ± 8.7	88.4 ± 2.2 [a]	75.8 ± 0.5[b]
Oat straw	91.8 ± 0.1	3.6 ± 0.3	1.57 ± 0.07	46.8 ± 7.9	136.2 ± 6.3	97.2 ± 0.5[a]	91.7 ± 0.4[b]
Soybean straw	91.3 ± 0.5	4.3 ± 0.1	1.44 ± 0.12	29.5 ± 2.2	137.7 ± 0.3	98.2 ± 0.1[a]	91.7 ± 0.0[b]
Corn stalks	91.5 ± 0.4	4.4 ± 0.3	1.41 ± 0.15	47.6 ± 10.5	170.1 ± 3.9	97.1 ± 0.6[a]	89.7 ± 0.2[b]
Alfalfa hay	89.7 ± 0.1	3.5 ± 0.1	1.52 ± 0.07	42.2 ± 5.5	215.0 ± 4.9	97.5 ± 0.3[a]	87.1 ± 0.3[b]
Leaves	87.3 ± 1.3	2.6 ± 0.2	1.63 ± 0.07	26.5 ± 1.5	332.8 ± 5.3	98.5 ± 0.1[a]	80.7 ± 0.3[b]
Wood shavings	99.4 ± 0.0	3.2 ± 0.4	1.76 ± 0.18	103.2 ± 2.6	97.0 ± 2.0	93.6 ± 0.2[a]	93.9 ± 0.1[a]
Turkey litter	72.1 ± 2.9	2.2 ± 0.2	1.40 ± 0.02	261.3 ± 3.3	476.4 ± 5.7	85.3 ± 0.2[a]	73.2 ± 0.3[b]

[a,b] Indicate statistically significant differences ($P < 0.01$).
[A] Volatile solids.
[B] Water holding capacity.
[C] Specific heat capacity at 27 °C.
[D] Air-filled porosity at dry condition.

2. Methods

2.1. Sample preparation and characteristics of materials

Twelve compost-bulking materials that could be potential cover materials in mortality composting systems were investigated for thermal property analysis. The characteristics of the materials are listed in Table 1. The materials with large particle size (corn stalks, oat straw, alfalfa hay, soybean straw, and wheat straw) were chopped to approximately 10 cm lengths for bulk material measurement. Materials were also ground to pass a 0.5 mm size screen for ground material measurement. The moisture content of each material was set into 6 levels based on water holding capacity (0, 20, 50, 80, 100% of WHC and saturated condition).

2.2. Moisture contents (MC), volatile solids (VS), water holding capacity (WHC)

Moisture contents throughout this study were measured by drying at 105 °C for approximately 24 h, while volatile solids were measured by combustion at 550 °C for 8 h (TMECC, 2002). A wet sample of known initial moisture content was weighed (W_I) and placed in a beaker. After soaking in water for 1–2 days and draining excess water through Whatman #2 filter paper, the saturated

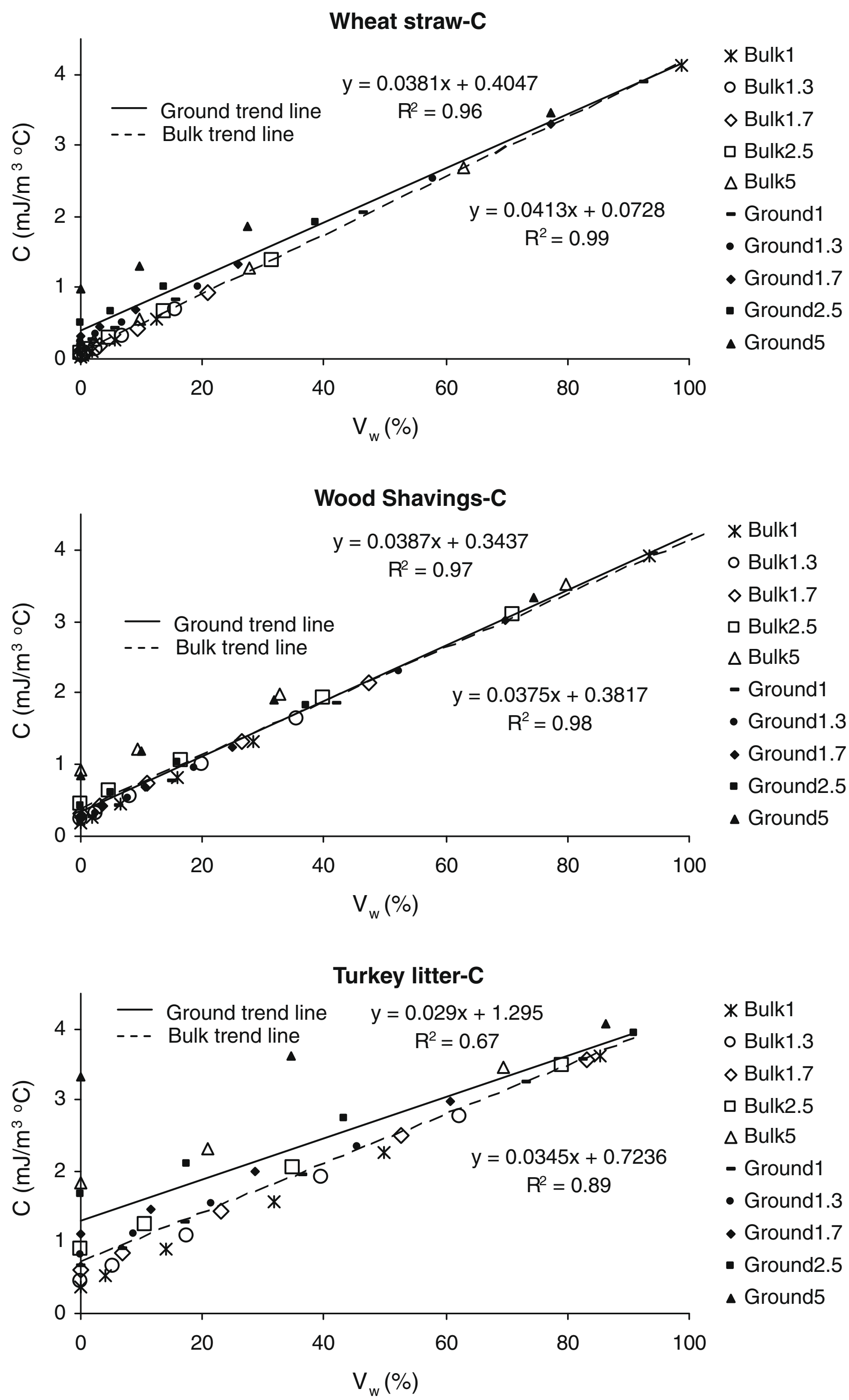

Fig. 1. Changes in volumetric heat capacity (C; error range 0–0.81 mJ/m^3 °C) with the volumetric water content (V_w), compaction (1, 1.3, 1.7, 2.5, 5 times uncompacted bulk density), and particle size (bulk and ground) of wheat straw, wood shavings, and turkey litter.

sample is weighed again (W_S). The amount of water retained by dry sample was calculated as the WHC. The water holding capacity (g·water/g·dry material) is calculated as

$$\mathrm{WHC} = \frac{\{(W_S - W_I) + \mathrm{MC}_I \times W_I\}}{\{(1 - \mathrm{MC}_I) \times W_1\}} \tag{7}$$

where MC_I = Initial moisture content of sample (decimal).

2.3. Bulk density

Bulk density was measured using an approximately 22-liter (bulk material) and 30 ml (ground material) volume container. The container was filled with material, and then the material was slightly compacted to ensure absence of large void spaces. The bulk density can be calculated by dividing the weight of the material by the volume of container.

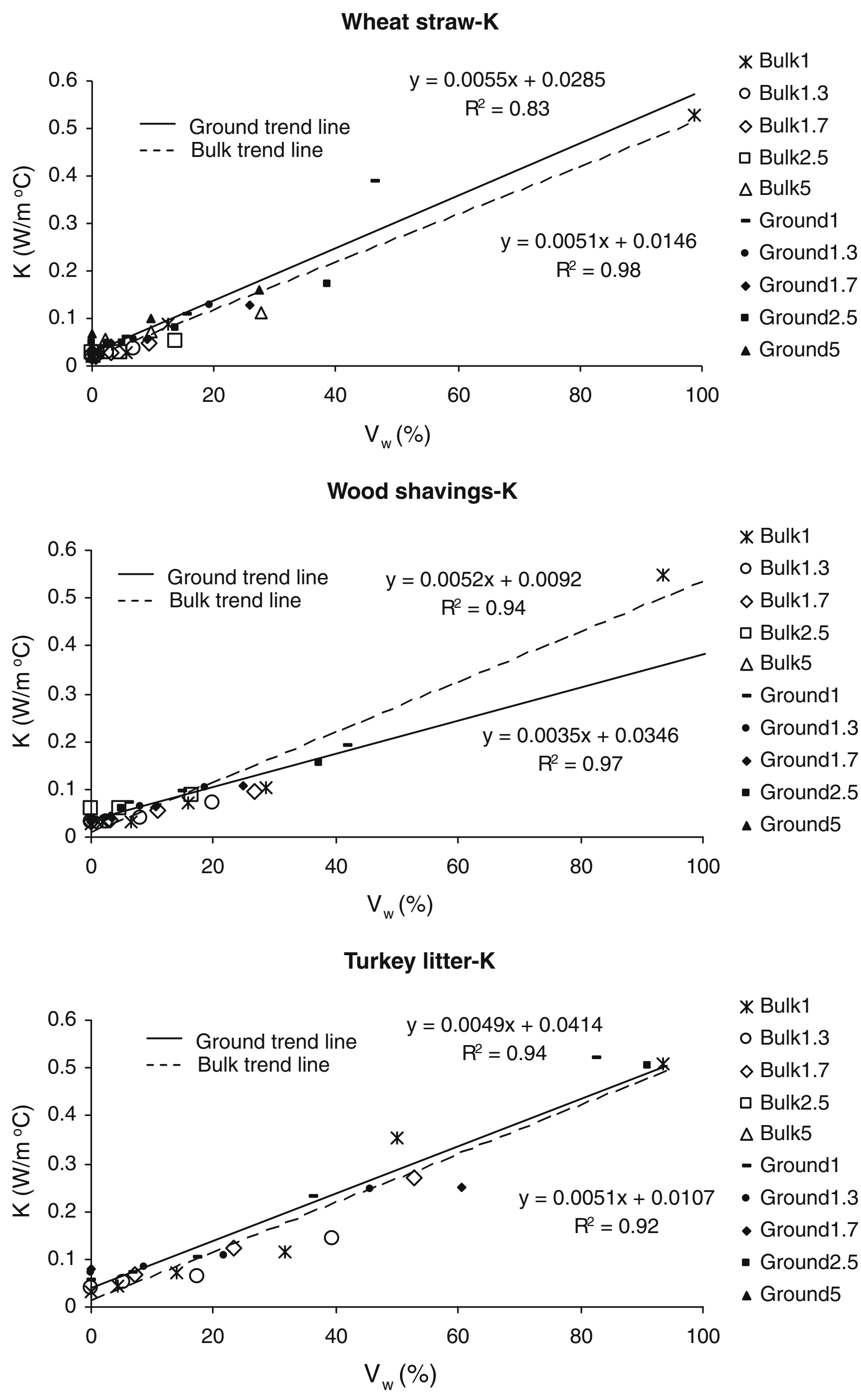

Fig. 2. Changes in thermal conductivity (K; error range 0–0.06 W/m °C) with the volumetric water content (V_w), compaction (1, 1.3, 1.7, 2.5, 5 times uncompacted bulk density), and particle size (bulk and ground) of wheat straw, wood shavings, and turkey litter.

2.4. Thermal property measurement with transient heat dissipation method

Thermal conductivity and thermal diffusivity were determined with transient heat dissipation device (KD2, Decagon, Pullman, WA, USA). They were measured at varying compaction (1, 1.3, 1.7, 2.5, and 5 times uncompacted bulk density), particle size (ground and bulk), and water content (0, 20, 50, 80% of water holding capacity and saturated condition). Material compaction was achieved by a mechanical pressing device that was developed to pack the sample down in the container. By turning a screw, the compaction level inside of a cylinder was adjusted.

2.5. Thermal conductivity measurement with steady state gradient method

Thermal conductivity was measured with steady state gradient method. Material filled in large box (46 × 51 × 8.9 cm) in direct contact with an anodized aluminum heat source plate on the bottom and heat sink plate on top. The four heater windings were distributed between grooves on the underside of the heat source plate to maintain a uniform plate temperature and the desired temperature gradient through the material. All four side walls were well-insulated to facilitate one-dimensional heat flow between the source and sink plates (Sauer et al., 2003).

Measurement of each material was conducted for about 7 days at flux density of 20–21 W/m^2. The measurement was done with dry material for the first half (about 3 days) and then with saturated material after filling the pore space with water.

The thermal conductivity (K, W/m °C) was obtained using Eq. (8).

$$K = \frac{q''L}{\Delta T} \tag{8}$$

where q'' is power input into the heat source plate (W/m^2), L is distance between the heat source and the heat sink plate (m), and ΔT is the temperature difference between the heat source and heat sink plate (°C).

Thermal conductivity of the material in steady state gradient measurement device was also measured by transient heat dissipation device (KD2) to compare the results of two different methods.

2.6. Specific heat capacity (C_p) and volumetric heat capacity

Specific heat capacity was measured with differential scanning calorimeter (DSC 220C, Seiko Instruments, Tokyo, Japan). The ground up, oven-dried sample weights ranged from 15 to 20 mg.

Table 2
Summary of thermal conductivity, volumetric heat capacity, and thermal diffusivity.

	Thermal conductivity W/m °C			Volumetric heat capacity MJ/m^3 °C			Thermal diffusivity mm^2/s		
	Dry	80% WHC	S[a]	Dry	80% WHC	S	Dry	80% WHC	S
Wheat straw	0.02–0.07	0.03–0.17	0.53	0.03–0.99	0.26–1.07	4.13	0.07–0.57	0.11–0.29	0.13
Sawdust	0.03–0.05	0.17–0.47	0.44	0.29–0.49	1.39–1.70	3.91	0.10–0.11	0.12–0.27	0.11
Soil compost blend	0.06–0.12	0.16–0.81	0.59	0.84–1.44	1.41–1.89	2.94	0.07–0.12	0.11–0.50	0.20
Silage	0.03–0.09	0.09–0.47	0.53	0.17–1.75	0.93–1.76	3.92	0.05–0.16	0.09–0.27	0.13
Beef manure	0.03–0.08	0.17–0.52	0.39	0.21–0.96	1.66–2.50	3.82	0.08–0.14	0.10–0.21	0.10
Oat straw	0.02–0.06	0.05–0.18	0.56	0.06–1.07	0.40–1.09	4.08	0.06–0.35	0.09–0.38	0.14
Soybean straw	0.02–0.07	0.06–0.30	0.54	0.05–0.99	0.28–1.32	4.10	0.07–0.44	0.09–0.30	0.13
Cornstalks	0.02–0.05	0.03–0.24	0.53	0.05–0.60	0.46–1.44	4.09	0.08–0.40	0.07–0.28	0.13
Alfalfa hay	0.03–0.05	0.07–0.15	0.43	0.05–0.82	0.37–1.54	4.09	0.07–0.55	0.09–0.33	0.11
Leaves	0.02–0.08	0.06–0.38	0.64	0.04–0.90	0.23–1.86	4.12	0.07–0.47	0.05–0.97	0.16
Wood shavings	0.03–0.06	0.07–0.15	0.55	0.17–0.85	0.77–0.99	3.92	0.07–0.18	0.09–0.16	0.14
Turkey litter	0.03–0.08	0.12–0.50	0.51	0.37–1.11	1.57–2.58	3.62	0.07–0.09	0.07–0.20	0.14

[a] Saturation.

Table 3
Comparison of thermal conductivity and thermal diffusivity values acquired by different methods.

	Thermal conductivity W/m °C				Thermal diffusivity mm^2/s			
	Dry		Saturation		Dry		Saturation	
	THD[a]	SSG[b]	THD	SSG	THD	C[c]	THD	C
Wheat straw	0.02 ± 0.00	0.13 ± 0.00	0.53 ± 0.01	0.47 ± 0.00	0.29 ± 0.01	0.57	0.11 ± 0.01	0.13
Sawdust	0.04 ± 0.01	0.11 ± 0.00	0.44 ± 0.09	0.45 ± 0.00	0.20 ± 0.02	0.29	0.11 ± 0.00	0.11
Soil compost blend	0.0680.01	0.24 ± 0.00	0.59 ± 0.06	0.59 ± 0.01	0.13 ± 0.01	0.12	0.13 ± 0.01	0.20
Silage	0.02 ± 0.01	0.15 ± 0.00	0.53 ± 0.01	0.51 ± 0.01	0.2880.02	0.16	0.1180.01	0.13
Beef manure	0.0480.01	0.2080.01	0.3980.04	0.5080.00	0.1880.03	0.14	0.10 ± 0.01	0.10
Oat straw	0.0380.01	0.1780.00	0.5680.01	0.84 ± 0.00	0.27 ± 0.01	0.33	0.1280.01	0.14
Soybean straw	0.02 ± 0.00	0.18 ± 0.00	0.5480.04	0.7080.00	0.2880.01	0.44	0.12 ± 0.01	0.13
Cornstalks	0.03 ± 0.01	0.11 ± 0.00	0.53 ± 0.03	0.46 ± 0.01	0.27 ± 0.00	0.40	0.11 ± 0.01	0.13
Alfalfa hay	0.02 ± 0.01	0.11 ± 0.00	0.43 ± 0.07	0.29 ± 0.00	0.27 ± 0.01	0.55	0.11 ± 0.01	0.11
Leaves	0.02 ± 0.01	0.23 ± 0.00	0.64 ± 0.09	0.8980.01	0.29 ± 0.02	0.47	0.15 ± 0.03	0.16
Wood shavings	0.02 ± 0.00	0.10 ± 0.00	0.55 ± 0.02	0.40 ± 0.00	0.27 ± 0.01	0.15	0.11 ± 0.01	0.14
Turkey litter	0.05 ± 0.00	0.20 ± 0.01	0.51 ± 0.01	0.5580.00	0.15 ± 0.01	0.08	0.12 ± 0.01	0.14

[a] Transient heat dissipation method.
[b] Steady state gradient method.
[c] Calculated value using thermal conductivity (THD) and volumetric heat capacity (DSC).

Measurement conditions were in the temperature range of room temperature to 60 °C, with temperature rising at a rate of 10 °C/min. Volumetric heat capacity (C) was obtained from the following calculation.

$$C = \rho C_P \tag{9}$$

Where ρ is bulk density (kg/m^3) and C_P is the specific heat capacity (J/kg °C).

3. Results and discussion

Thermal conductivity and volumetric heat capacity of wheat straw, wood shavings, and turkey litter as a function of volumetric water content, bulk density, and particle size are shown in Figs. 1 and 2. As seen in Figs. 1 and 2, generally, the thermal conductivity and volumetric heat capacity increased with increasing moisture content and bulk density. Theoretically, these values can be predictable because the thermal conductivity and volumetric heat

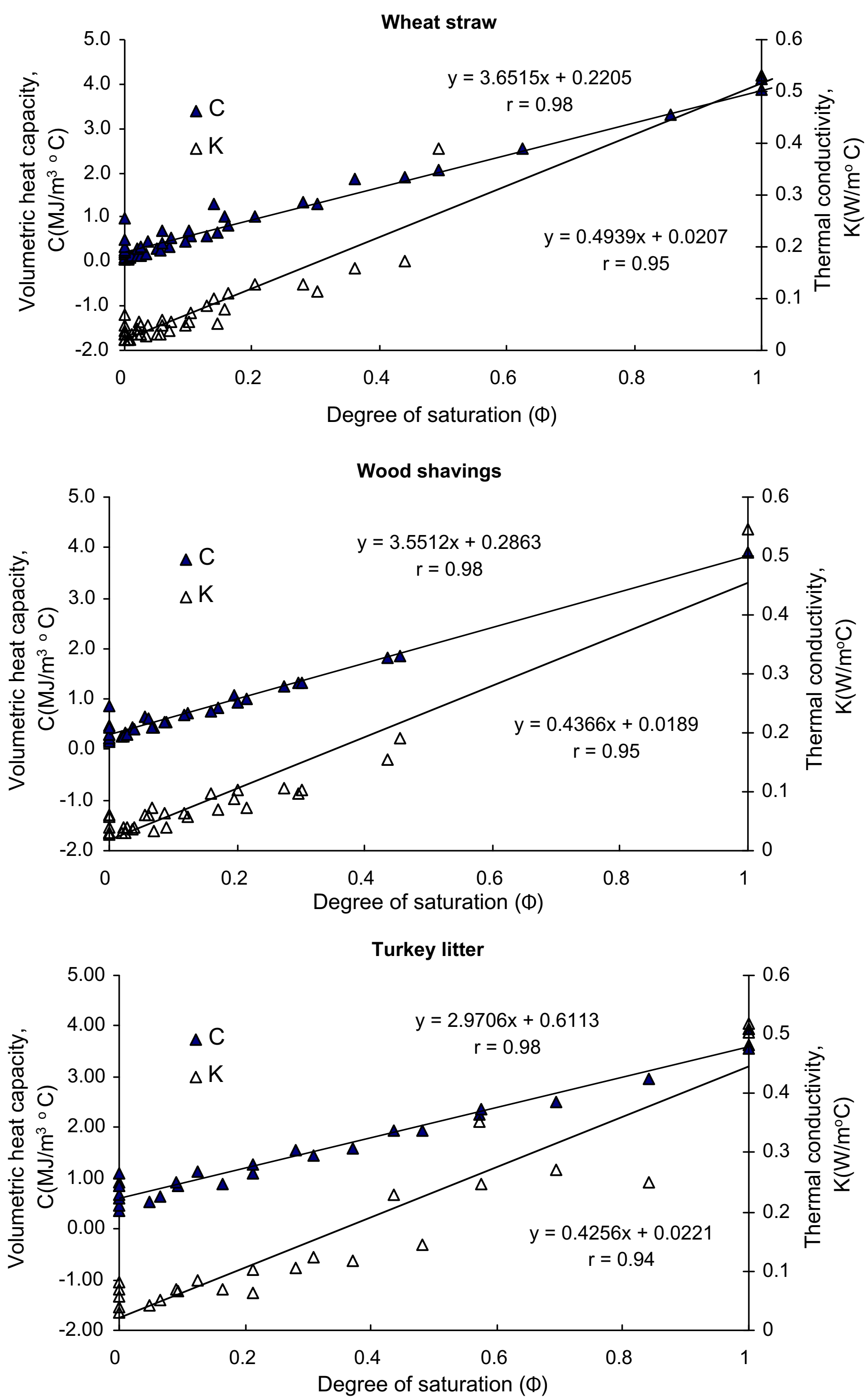

Fig. 3. Changes in volumetric heat capacity (C; error range 0–0.81 mJ/m^3 °C) and thermal conductivity (K; error range 0–0.06 W/m °C) with the degree of saturation (Φ) of wheat straw, wood shavings, and turkey litter.

capacity of water (0.6 W/m °C, 4.18 MJ/m^3 °C) are greater than those of air (0.025 W/m °C, 0.001 MJ/m^3 °C) (Jiang et al., 1986; Holman, 2002; Labance et al., 2006). Since the portion of the pore space filled with water increases with increasing moisture content and decreases with increasing bulk density, the reduced volume fraction of air, which has relatively lower thermal conductivity and volumetric heat capacity than water and solid materials finally, causes this difference.

A small increase of thermal conductivity and volumetric heat capacity with grinding was observed for all materials except wood shavings. These changes may be explained by considering the air-filled porosity change with grinding. The air-filled porosity of grain like materials generally increases as the particle size decreases but straw-like materials and the materials which have large particles show reverse results (Abu-Hamdeh et al., 2000). All of the materials showed air-filled porosity decrease except wood shavings, as seen in Table 1.

The thermal properties of 12 materials determined using transient heat dissipation method and differential scanning calorimeter are summarized in Table 2. The range of each thermal property represents the minimum and maximum values observed by varying bulk density and particle size under fixed moisture content.

Dry and saturated conditions are not realistic moisture contents of composting materials. Since the optimum moisture content of compost material is observed near the WHC, thermal property values at 80% of WHC may be used as a standard of practical thermal properties (Ahn et al., 2008b). Thermal conductivity and volumetric heat capacity of saw dust, soil compost blend, beef manure, and turkey litter showed the highest values at 80% of WHC; K (0.12–0.81 W/m °C) and C (1.36–4.08 MJ/m^3 °C). Silage showed medium values: K (0.09–0.47 W/m °C) and C (0.93–3.09 MJ/m^3 °C). Wheat straw, oat straw, soybean straw, cornstalks, alfalfa hay, and wood shavings showed the lowest values: K (0.03–0.30 W/m °C) and C (0.26–3.45 MJ/m^3 °C).

As mentioned above, thermal conductivity and volumetric heat capacity of all materials increased linearly with increasing moisture content and bulk density, but the relationship between calculated thermal diffusivity and both factors is complex. Hypothetically, the thermal diffusivity of all materials should decrease with increasing moisture content because the thermal diffusivity of water (0.147 mm^2/s) is lower than that of air (23.5 mm^2/s) (Kreith and Black, 1980; Jiang et al., 1986; Labance et al., 2006). However, measured values did not show this consistent relationship with moisture content and bulk density. Ascending, descending, and mixed trends of the relationship between thermal diffusivity and moisture content have been reported (Houkom et al., 1974; Verdonck et al., 1978; Jiang et al., 1986; Dutta et al., 1988; Bristow, 1998; Iwabuchi et al., 1999; Labance et al., 2006; Opoku et al., 2006). Bulk density shows relatively more significant increases than thermal conductivity when moisture content is increased, which may explain the descending trends and vice versa. Since thermal diffusivity depends on the interaction between thermal conductivity, bulk density, and volumetric heat capacity, it shows complex trends with respect to moisture content and bulk density (Yang et al., 2002).

The thermal conductivity and thermal diffusivity values measured with different methods under dry and saturated conditions at natural bulk density are shown in Table 3. The transient heat dissipation method was used for both thermal conductivity and diffusivity measurements. The steady state gradient method was used for thermal conductivity measurements. Thermal conductivity was measured with the transient heat dissipation method and volumetric heat capacity measured with differential scanning calorimeter were used for the thermal diffusivity calculation. Thermal conductivity and thermal diffusivity of saturated materials showed no difference between different methods and materials because it is the water content that dominates the thermal properties at saturation. However, thermal conductivity of dry materials measured with the transient heat dissipation method showed lower values than that with the steady state gradient method. Thermal diffusivity of dry materials measured with transient heat dissipation method showed no specific relationship with calculated values.

Table 4
Linear regression and correlation coefficient for the relation between thermal conductivity and degree of saturation and volumetric heat capacity and degree of saturation.

Materials	Volumetric heat capacity[a]		Thermal conductivity[b]	
	Linear regression	r	Linear regression	r
Wheat straw	$C = 3.65\ \Phi + 0.22$	0.98	$K = 0.49\ \Phi + 0.02$	0.95
Sawdust	$C = 3.38\ \Phi + 0.29$	0.99	$K = 0.43\ \Phi + 0.03$	0.99
Soil compost blend	$C = 1.81\ \Phi + 1.06$	0.95	$K = 0.80\ \Phi + 0.05$	0.84
Silage	$C = 3.13\ \Phi + 0.47$	0.95	$K = 0.39\ \Phi + 0.03$	0.89
Beef manure	$C = 3.29\ \Phi + 0.44$	0.98	$K = 0.43\ \Phi + 0.03$	0.94
Oat straw	$C = 3.76\ \Phi + 0.22$	0.97	$K = 0.45\ \Phi + 0.02$	0.93
Soybean straw	$C = 3.73\ \Phi + 0.19$	0.98	$K = 0.48\ \Phi + 0.02$	0.95
Cornstalks	$C = 3.67\ \Phi + 0.20$	0.99	$K = 0.41\ \Phi + 0.02$	0.94
Alfalfa hay	$C = 3.70\ \Phi + 0.24$	0.98	$K = 0.38\ \Phi + 0.03$	0.94
Leaves	$C = 3.82\ \Phi + 0.24$	0.97	$K = 0.45\ \Phi + 0.03$	0.85
Wood shavings	$C = 3.55\ \Phi + 0.29$	0.98	$K = 0.44\ \Phi + 0.02$	0.95
Turkey litter	$C = 2.97\ \Phi + 0.61$	0.98	$K = 0.43\ \Phi + 0.02$	0.94

[a] Measured by differential scanning calorimeter.
[b] Measured by transient heat dissipation method.

In order to represent the relationship of thermal properties versus water content, bulk density, and particle size, regression analyses were carried out for thermal conductivity and volumetric heat capacity as a function of each factor and combined factors. Although, both thermal properties showed a linear relationship with each factor (Figs. 1 and 2), the relationship with combined factors showed an unspecific trend. As practical composting processes occur under the various interactions between each factor, it is important to get a representative model that considers all factors.

The concept of degree of saturation (Φ), suggested by Chandrakanthi et al. (2005), is used in this paper to show the combined effects of three factors on thermal conductivity and volumetric heat capacity. The thermal conductivity and volumetric heat capacity of wheat straw, wood shavings, and turkey litter showed linear relationships with the degree of saturation (Φ), as seen in Fig. 3.

The regression calculations of 12 materials between thermal conductivity, volumetric heat capacity, and degree of saturation are shown in Table 4. The correlation coefficient (r) values for all regression calculations between volumetric heat capacity and Φ ranged from 0.95 to 0.99. The linear regression calculations between thermal conductivity and Φ yielded r values between 0.84 and 0.99. The first order regression models developed in this paper represented the relationship of Φ versus thermal conductivity and volumetric heat capacity well. If the parameters of moisture content (MC), organic matter (OM), and bulk density are known, thermal properties of 12 compost bulking materials can be predicted using the first order regression models in Table 4.

4. Conclusions

The following conclusions were drawn based on the experimental study of thermal properties of 12 compost bulking materials at a range of moisture contents, bulk densities, and particle sizes with different methods.

The thermal conductivity and volumetric heat capacity showed a linear relationship with water content, bulk density, and particle size but the thermal diffusivity showed a nonlinear relationship as many previous researchers reported.

A representative model considering all combined factors is necessary to manage various interactions between each factor in an actual composting processes. The interaction between volumes of water, air, and solids under the various combinations of moisture content, bulk density, and particle size is best illustrated by the degree of saturation.

The first order regression models developed in this paper represent the relationship of degree of saturation versus thermal conductivity and volumetric heat capacity well. Once the parameters of moisture content, organic matter and bulk density are known, the first order regression models can predict the thermal properties of 12 compost bulking materials. The resulting thermal properties of compost bulking materials can be used to develop heat transport models for the design of more optimal temperature control in composting systems.

Acknowledgements

The publication of this document has been funded in part by the Iowa Department of Natural Resources through a Grant from the US Environmental Protection Agency under the Federal Nonpoint Source Management Program (Section 319 of the Clean Water Act). The authors wish to acknowledge Dr. Michael Thompson of Iowa State University for providing access to a DSC instrument and operational assistance.

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